# Thermal Conductivity of Zr-2.5% Nb

## Preliminary Recommendation

The preliminary recommendation for the α-phase thermal conductivity of Zr-2.5% Nb tubes in the axial direction is an equation obtained from a combined fit of three sets of axial thermal conductivity data from measurements by the Chinese Institute of Atomic Energy (CIAE)[1] and two sets of axial thermal conductivity data obtained by Atomic Energy of Canada Limited (AECL) that have been tabulated in the IAEA report "Thermophysical properties of materials for water reactors"[1].

For the α-phase (500-1100 K),

$$\lambda \ (W{\cdot}m^{-1}{\cdot}K^{-1}) \ = \ 16.85 - 2.186 \times 10^{-3}\, T \ + \ 8.899 \times 10^{-6}\, T^2 \qquad \textbf{(1)}$$

Equation (1) fits the CIAE and AECL α-phase axial thermal conductivity data [1] with a standard deviation of 0.52 W $m^{-1}$ $K^{-1}$. Although the AECL circumferential thermal conductivity data were not included in the data used to obtain Eq.(1), this equation is a good approximation to the α-phase circumferential thermal conductivity of Zr-2.5% Nb. Figure 1 shows that the AECL thermal conductivity data in the circumferential direction are all within the 5% uncertainty for this equation.

The preliminary recommendation for the β-phase thermal conductivity of Zr-2.5%N is an equation estimated from the three highest temperature data from CIAE measurements and the equation for the thermal conductivity of Zr-1%Nb in the β-phase obtained from measurements by Peletsky and Petrova [2].

For the β-phase from 1130-1600 K,

$$\lambda \ (W{\cdot}m^{-1}{\cdot}K^{-1}) \ = \ 5.0 \ + \ 0.020\, T \qquad \textbf{(2)}$$

Values calculated with these equations are shown in Figure 1 along with estimated uncertainties (dotted lines) and the axial and circumferential (Circ) pressure tube thermal conductivity data for Zr-

2.5%Nb from measurements by the Chinese Institute of Atomic Energy (CIAE) and from measurements by Atomic Energy of Canada, Ltd.(AECL). Thermal conductivity values for Zr-2.5% Nb as a function of temperature are given in Table 1.

## Uncertainty

The uncertainty shown in Figure 1 for the α-phase axial thermal conductivity is 5%. This uncertainty is sufficient to include the deviations from the recommended equation for all axial and circumferential experimental data except for one CIAE low temperature datum, which is low by 7.5%. Thus, this uncertainty represents the error in the fit and experimental uncertainties indicated by the scatter in the data. For the β-phase, the uncertainty in the recommended equation is 15%. This uncertainty is sufficient to include the Zr-1%Nb thermal conductivity data, which represent a lower limit for the thermal conductivity of Zr-2.5%Nb.

## Discussion

**α-phase**: Measurements of the thermal conductivity of Zr-2.5%Nb have been made by the Chinese Institute of Atomic Energy (CIAE) and Atomic Energy of Canada, Ltd. (AECL) [1]. The data reported by the Chinese Institute of Atomic Energy are from measurements by W. Li et al. [3] The data reported by the Atomic Energy of Canada, Ltd.[1] are from measurements by Price et al.[4] and by Mills et al.[5]. Figure 2 shows all the available data [1]. Data from the Chinese Institute of Atomic Energy thermal conductivity measurements in the axial direction on Zr-2.5%Nb pressure tubes annealed at three different temperatures, 673 K, 1073 K, and 1173 K are labeled respectively "CIAE 1 Tube Axial", "CIAE 2 Tube Axial", and "CIAE 3 Tube Axial" [1]. The Atomic Energy of Canada, Ltd thermal conductivity data shown in Figure 2 are labeled AECL. They are:

"AECL 1 Tube Axial" is the axial thermal conductivity of a cold-worked pressure tube;
"AECL 2 Rod Long" is the longitudinal thermal conductivity of a cold-worked rod;
"AECL 3 Tube Axial" is the axial thermal conductivity of a heat-treated pressure tube;
"AECL 4 Tube Circ" is the circumferential thermal conductivity of a cold-worked pressure tube;

"AECL 5 Tube Circ" is the circumferential thermal conductivity of a heat-treated pressure tube.

Figure 2 indicates that the longitudinal thermal conductivity of rods is consistently higher than that of pressure tubes in either the axial or circumferential directions. The circumferential pressure tube thermal conductivities appear to be consistent with that in the axial direction below 500 K. However, between 500 and 700 K, the circumferential thermal conductivities are slightly lower than those in the axial direction. Consequently, the circumferential thermal conductivity data have not been grouped with the axial data to obtain an equation for the thermal conductivity of pressure tubes in the axial direction. Differences due to heat treatment do not appear to be large. Figure 2 shows that the data at 372 K, 489K, and 520 K for the CIAE sample annealed at 673 K are inconsistent with the other axial thermal conductivity data. Thus these data have not been included in the least squares fit to the Zr-2.5%Nb axial thermal conductivity data. The three CIAE data above 1100 K have also not been included in the fit because they appear to belong to a separate set and most likely represent measurements in the β-phase. Equation (1) is a least squares fit to the axial thermal conductivity data from 300 K to 1100 K excluding the three lowest temperature CIAE data from sample 1, which was annealed at 673 K. The data fit and resulting equation are shown in Figure 3.

Figure 4 shows the recommended equation for the thermal conductivity of Zr-2.5%Nb alloy in the axial direction, the AECL and CIAE data reported in the IAEA report [1], and equations recommended in a Russian Academy of Sciences Nuclear Safety Institute (IBRAE) report by Ozrin et al.[6] The IBRAE equations, which are also given in the IBRAE database on the World Wide Web, were obtained by fitting data reported by W. Li et al. at the First Asian Thermal Physical Properties [3]. This is the same source that was reported in the IAEA report [1] for the CIAE data tabulated in that report. The IBRAE equations appear to be labeled incorrectly in that the IBRAE "radial" equation goes through the CIAE and AECL axial data whereas the IBRAE "axial"equation passes through the AECL data for a rod in the longitudinal direction. The equation recommended by IBRAE for Zr-1%Nb based on measurements by Peletsky and Petrova[2] has also been included in Figure 4.

**β-phase:** An equation to represent the β-phase thermal conductivity of Zr-2.5%Nb has been estimated from the CIAE data above 1100 K and the equation which represents the β-phase Zr-1%Nb thermal conductivity data of Peletsky and Petrova [2]. Figure 4 shows that from above 850 K the thermal conductivity of Zr-1%Nb has a slope that is similar to that for Zr-2.5%Nb but the thermal conductivity of Zr-1% Nb is lower in magnitude than that for Zr-2.5% Nb. Thus, a reasonable assumption for the β-phase is that the thermal conductivities for both compositions have the same slope but are displaced by a constant equal to the difference in the thermal conductivities at approximately 1130 K. The equation that fits the data of Peletsky and Petrova[2] for the β-phase thermal conductivity of Zr-1%Nb is:

$$\lambda \ (W{\cdot}m^{-1}{\cdot}K^{-1}) \ = \ 1.51 \ + \ 0.020\,T \tag{3}$$

Equation (3) gives a thermal conductivity of 24.1 $W{\cdot}m^{-1}{\cdot}K^{-1}$ at 1030 K. The mean of the two CIAE data at 1130 K is 27.6 $W{\cdot}m^{-1}{\cdot}K^{-1}$. These values were used to obtain the constant in Eq.(2). Figure 5 shows the data for Zr-2.5% Nb, Zr-1%Nb, and the recommended equations for Zr-2.5%Nb and the equations recommended for Zr-1%Nb thermal conductivity that are a fit to the data of of Peletsky and Petrova [2] and given in the IBRAE report [6] and IBRAE database on the World Wide Web. and are

**References**


1. J. Cleveland, ed., *Thermophysical properties of materials for water cooled reactors*, International Atomic Energy Agency Technical Document **IAEA-TECDOC-949**, Vienna, Austria (June 1997).

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3. W. Li, Lili Zhang, Guanyu Cui, and Baolai Qi , *Thermal Diffusivity and Conductivity of Zirconium Alloy,"* Proc. of the First Asian Thermal Physical Properties Conf. April 21-241986, Beijing, China, pp. 665-670, Acad. Publ. (1986); as referenced in **IAEA-TECDOC-949** (reference 1).

4. .E. G. Price, *Thermal Conductivity, Electrical Resistivity, and Specific Heat of CANDU Construction Alloys and AISI Type 403 End Fitting*, **TDVI-368** (1980); as referenced in **IAEA-TECDOC-949** (reference 1).

5. W. Mills, M. H. Schankula, and B. A. Lange, *The Thermal Conductivity of Zirconium, Zircaloy-2, and Zirconium-2.5wt% Niobium and Some of Their Hydrides from 150*$^o$C to 350$^o$C, AECL Internal Document; as referenced in **IAEA-TECDOC-949** (reference 1).

6. V. T. Ozrin, V. Yu Zitcerman, V. M. Gefter, and V. F. Bajbuz, *Material Proeprties for International Nuclear Safety Data Base*, Russian Academy of Sciences Nuclear Safety Institute (IBRAE) report **NSI-SARR-34-96** (September 1996).

**Table 1  Thermal Conductivity of Zr-2.5% Nb**

| Temperature K | Thermal Conductivity $W\ m^{-1}\ K^{-1}$ |
|---|---|
| 300 | 17.0 |
| 400 | 17.4 |
| 500 | 18.0 |
| 600 | 18.7 |
| 700 | 19.7 |
| 800 | 20.8 |
| 900 | 22.1 |
| 1000 | 23.6 |
| 1100 | 25.2 |
| 1200 | 29.0 |
| 1300 | 31.0 |
| 1400 | 33.0 |
| 1500 | 35.0 |
| 1600 | 37.0 |

Fig. 1 Recommended Axial Thermal Conductivity of Zr-2.5%Nb

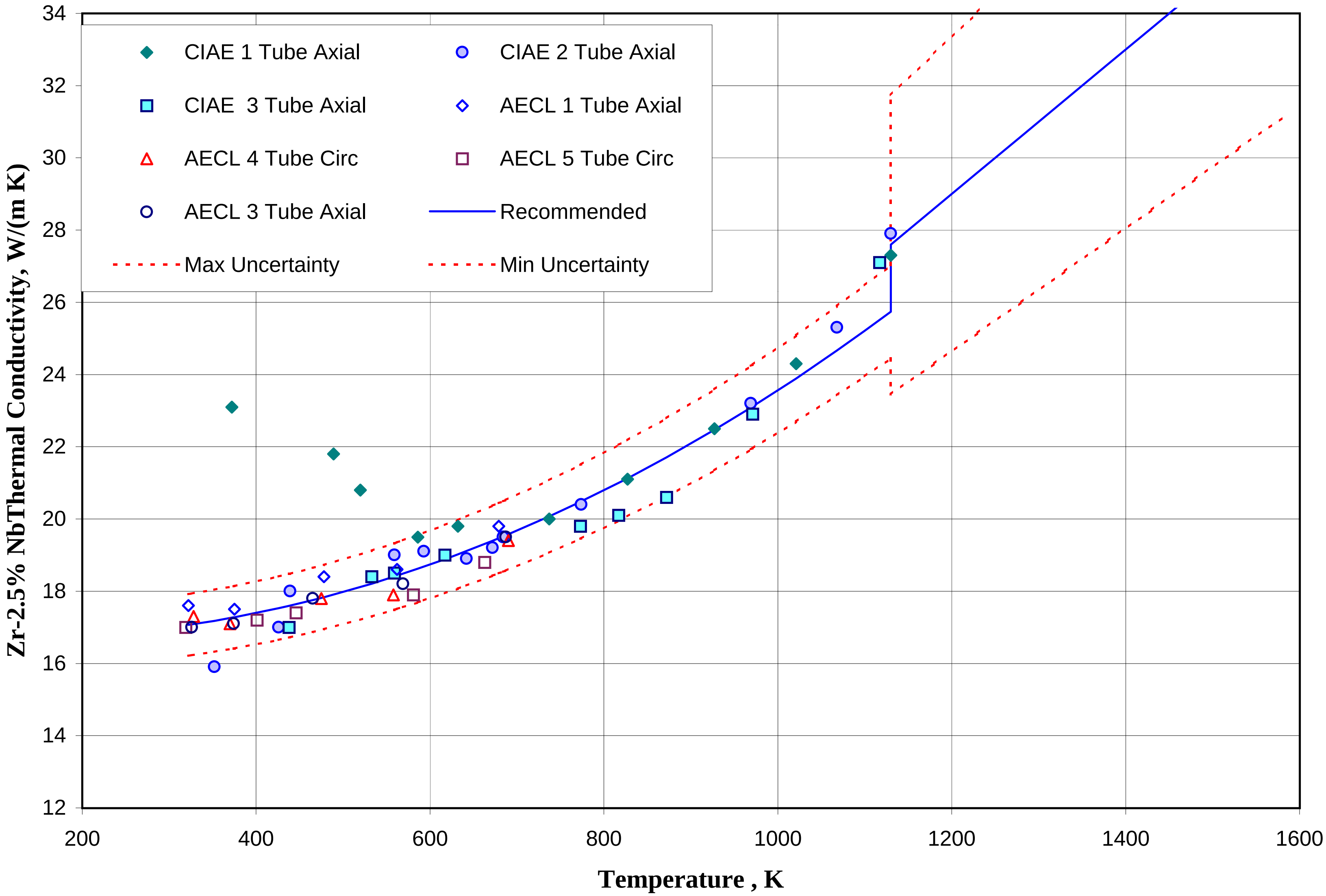
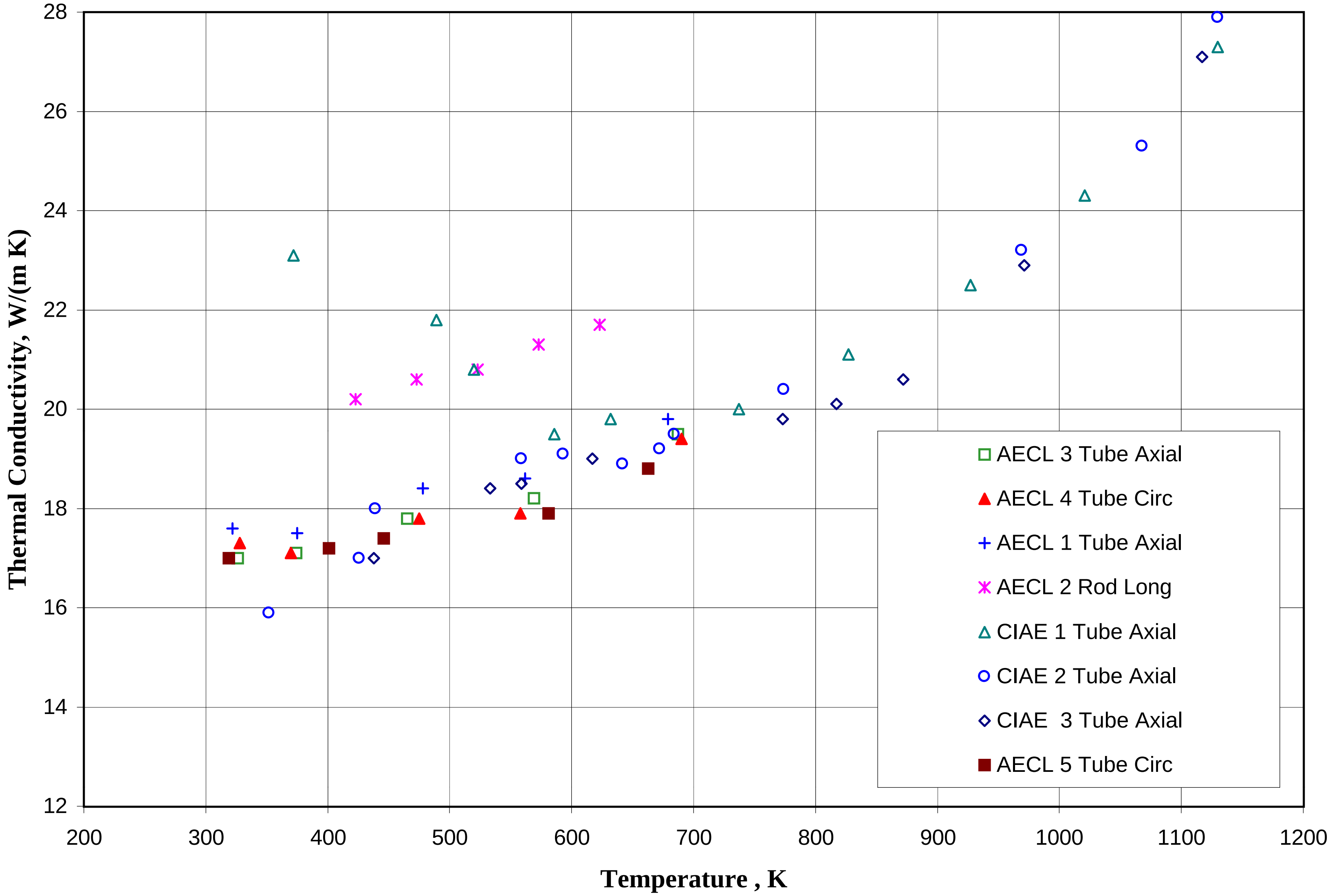


Fig. 2  Available Data for the Thermal Conductivity of Zr-2.5% Nb



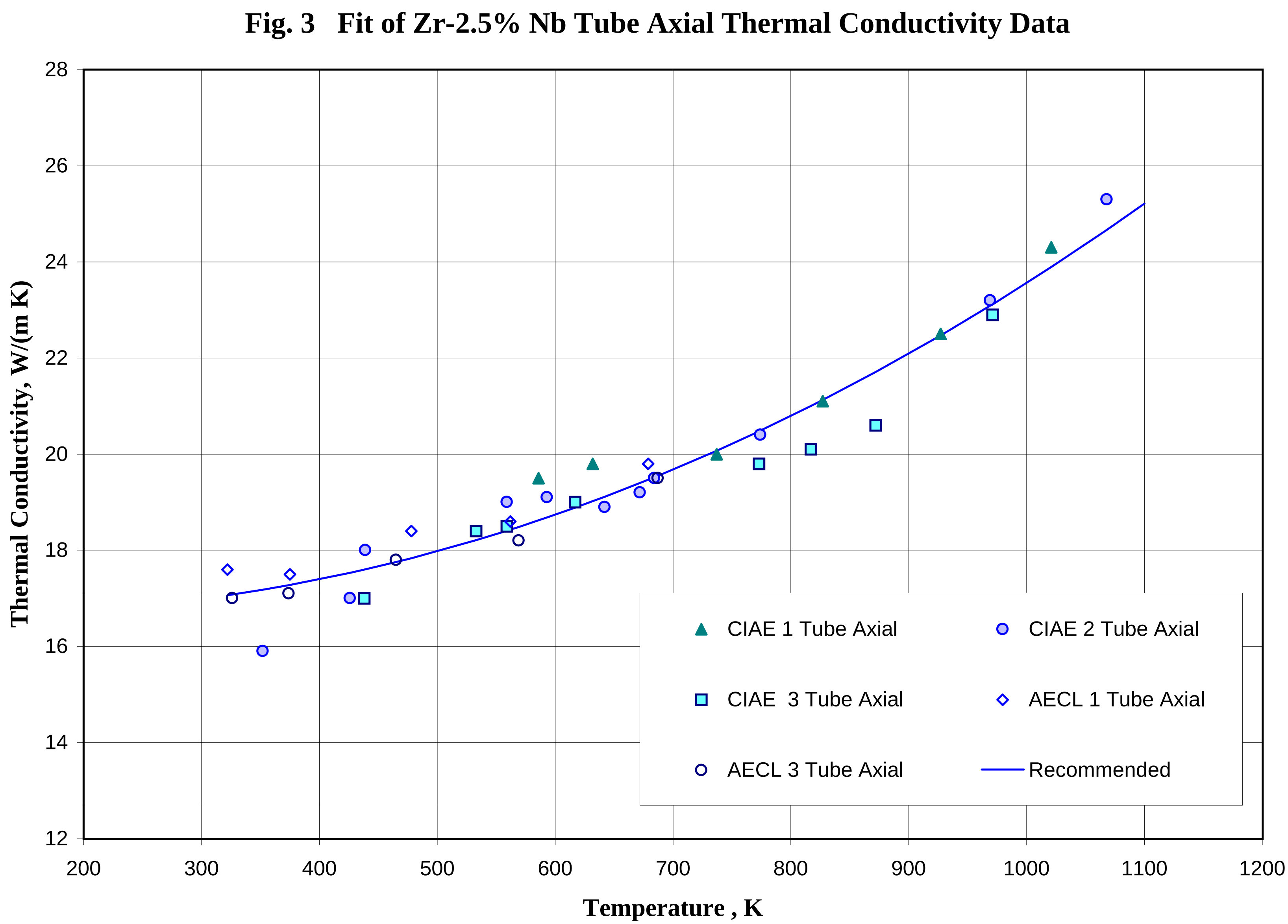
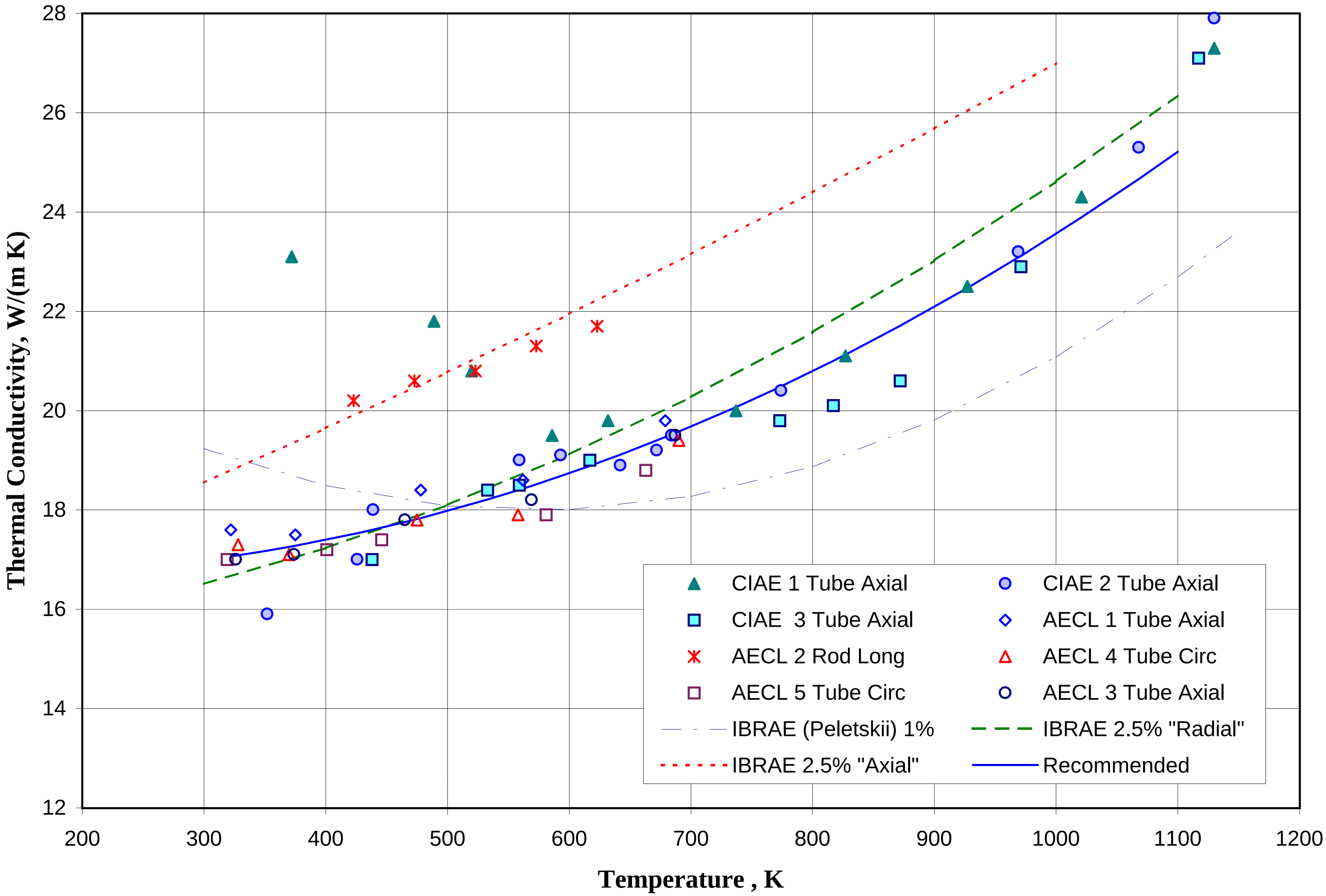


Fig. 3 Fit of Zr-2.5% Nb Tube Axial Thermal Conductivity Data
Thermal Conductivity, W/(m K)
Temperature , K
28
26
24
22
20
18
16
14
12
200
300
400
500
600
700
800
900
1000
1100
1200
CIAE 1 Tube Axial
CIAE 2 Tube Axial
CIAE 3 Tube Axial
AECL 1 Tube Axial
AECL 3 Tube Axial
Recommended

Fig. 4 Thermal Conductivity of Zr-2.5% Nb



# Fig. 5 Thermal Conductivity of Zr-Nb